ROLAND EÖTVÖS AND PALEOMAGNETISM

With 3 figures

by

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SUMMARY

At the end of the previous century Roland *Eötvös* investigated by the aid of his translatometer the remanent magnetism of earthenwares and stamped bricks. From the measured components of the remanent moment he determined the angle of inclination contemporary to the burning. It is interesting, that he found negative inclinations for the centuries B. C. – similarly to the data found before him by the Italian *Folgheraiter*.

Eötvös investigated with his translatometer in each case the magnetization of rocks which caused magnetic anomalies. He constructed also a device, which is in steady use, for taking oriented samples.

He did not publish his translatometer-method for the determination of the induced and remanent magnetic moment. The author makes known the practice followed by the Eötvös Geophysical Institute, and shows the method how to calculate declination and inclination of past times from measurements made by the translatometer.

It has been well known a good while back that *fired clay products* get magnetized in the earth's magnetic field in the direction of the field during their cooling after being burnt out and they retain their magnetism as *remanent magnetism* with a great stability. Thus these fired clay products may keep at least the *direction* of the geomagnetic field prevailing during their firing (more correctly speaking: during their cooling), hence providing a possibility for the determination of the direction of the ancient geomagnetic field, taking into account the remanent magnetisation of the clay product and its site during the firing process.

The Italian Folgheraiter investigated the remanent magnetization of *Etruscan ceramic relics* from this point of view. Obviously, such earthen vessels had been standing upright when being burnt, therefore the vertical direction may be marked on them easily, though their horizontal directional site might be varied. Thus the direction of their remanent magnetization can only indicate the angle between the direction of the ancient magnetic field and the vertical, respectively its complementary, i. e. the *inclination*, while the declination, which characterises the direction of the horizontal projection of the field-vector remains unknown. Folgheraiter based his conclusions concerning the direction of the remanent magnetization of the ceramic vessels – and concerning so the inclination prevailing during their burning – on the distribution of the *free magnetism* manifesting itself on the surface of these vessels. He found that in Italy in the 8^{th} century B. C. the inclination was small and its *direction was opposite* to the actual, going through zero a few centuries later and turning after all to *positive values* now prevailing.[1]

In Hungary Roland Eötvös conducted investigations of this kind, using a more developped method – not only on ceramic vessels, but on *baked bricks*, too. It is namely well known in the case of marked bricks, on wich side they come to lie during their firing, while their directional position in the horizontal plane could be varied. Therefore this kind of investigation is able also to define only the *inclination of ancient times*. Eötvös did not consider the distribution of the free magnetism, but he determined the components of the remanent magnetic moment by his sensitive *magnetic translatometer*. The resultant of these gave him the direction of the resultant magnetization from which the magnetic inclination of those times could be computed. His main results were as follows:

Era	Inclination
B. C. IV. century	– 35°
,, III. ,,	– 20°
A. D. about 1400	58°
,, 1669	72°
,, 1748	68°
,, 1870	62°

As we see the inclination had been also *negative* in Hungary in the centuries B. C., it turned to be zero in one of the first centuries A. D. and it has been remaining positive since then reaching its maximum value at the end of the 17^{th} century.

The principle of the procedure and the results for the inclination were not published by Eötvös in print but they had been dealt with in the session of the Hungarian *Mathematical and Physical Society* on the 1^{st} February, 1900. The lecture was reviewed by Alexander Mikola in the *Gazette of Natural Sciences*.[2] According to this Eötvös had the intention to continue the investigation and he wanted to concentrate especially on clay products of the first millenium A. D. We have no further information on this matter.

At a later date – in his report presented to the General Conference of the International Geodetic Association in 1909 – Eötvös published the susceptibility-data of some rock samples from the Fruska-Gora mountains.[3] He promised a more intensive investigation of the magnetization of these rocks and the explanation of this method but he could not keep his promise in his life time. His method of determining susceptibility and remanent magnetic moment was briefly dealt with by Eugene Fekete in the

Eötvös *Memorial Number of the Mathematical and Physical Journal* (of Hungary),[4] nevertheless no details were given.

Eugen Fekete also told that Eötvös had constructed a simple *magnetic compass,* too, to sample some rocks for the purpose of such investigations. By means of this instrument the position of the sample in its site, its orientation respectively the north, the east and vertical direction can be marked and so the three rectangular components of the magnetic moment can be determined. We know that the remanent magnetization of eruptive rocks is also the result of the magnetization obtained during the cooling process following the state of outflowing hot lava and stabilized afterwards. Therefore the determination of the remanent magnetization of such *oriented rock samples* may lead us to the information about the direction of the magnetic field intensity being active in the era of rock-genesis. On the other hand if we know the geological era in which the magnetic field assumed a given direction, we are in the position to compute the era of the origin of the rock (showing the remanent magnetization dealt with) and so the time of eruption of the volcano as well.

This method of investigation of rock magnetism is widely applied nowadays under the name of *paleomagnetic research.* We may state therefore that Eötvös with his investigations of the remanent magnetization of oriented rock samples quite closely approached to this modern branch of research, nevertheless we have no information about whether he attempted to apply his method to the determination of the magnetization of geological eras or to the determination of the age of rock genesis.

* * *

The above mentioned instrument of Eötvös had been called magnetic translatometer by him because it is suitable to measure the *translational force* exerted upon magnetic bodies. It is well known that in a homogeneous magnetic field magnetic bodies are affected only by rotational or directing force. A translational — attractive or repelling — action can only be present in case of an *inhomogeneous magnetic field.* If we denote the rectangular components of the magnetic field intensity by X, Y, Z, the derivatives with respect to the coordinates x, y and z by the respective indices, then the inhomogeneity of the magnetic field is characterized by the components of the following gradient-vectors:

$$\begin{aligned} \text{grad } X &= (X_x, \ X_y, \ X_z) \\ \text{grad } Y &= (Y_x, \ Y_y, \ Y_z) \\ \text{grad } Z &= (Z_x, \ Z_y, \ Z_z) \end{aligned}$$

Further we know that the *components of the translational force* acting in the inhomogeneous magnetic field upon the magnetic body with the moment $\mathfrak{M}(M_x, \ M_y, \ M_z)$ are the scalar products of the $\mathfrak{M}$ moment of the magnet and of the gradient-vector of the individual components of the field intensity:

$$\begin{aligned} P_x &= (\mathfrak{M}, \text{grad } X) = M_x X_x + M_y X_y + M_z X_z \\ P_y &= (\mathfrak{M}, \text{grad } Y) = M_x Y_x + M_y Y_y + M_z Y_z \\ P_z &= (\mathfrak{M}, \text{grad } Z) = M_x Z_x + M_y Z_y + M_z Z_z \end{aligned}$$

The magnetic translatometer of Eötvös is based on the principle of the Coulomb-balance. In its form it is like the horizontal gravitational variometer of Eötvös — the Eötvös-balance of today — with the usual weighing mass on the one end of the balance beam and with the small magnet suspended on the other end. (Fig. 1.) Obviously, upon the balance beam hanging on a vertical wire only horizontal forces, therefore only the *horizontal components* P_x and P_y of the translational force exerted in the inhomogeneous field will be acting, thus producing a rotational couple. According to this the instrument is suitable to measure the horizontal components P_x and P_y of the translational magnetic force. In the original form of the instrument the inclination of the measuring magnet to the horizontal plane could be varied. Eötvös has shown that if we make the measurement both with a magnet inclined under the angle i downwards and then upwards, we obtain components P_x, P_y and P'_x, P'_y from which the quantities

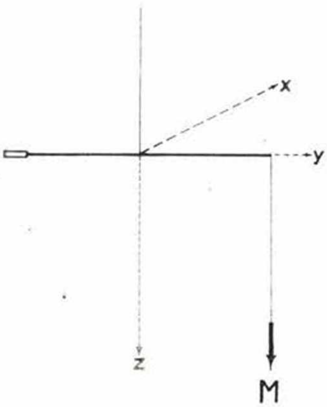

Fig. 1.

$$X_x,\ X_y = Y_x, \quad X_z = Z_x \quad \text{and} \quad Y_z = Z_y$$

i. e. *4 of the 6 data* needed for the characterization of the inhomogeneity of the magnetic field can be determined. (As a matter of course we have to measure and to take into account the rotational couple originated from the inhomogeneity of the gravitational field, too.)[5]

Later on Eötvös made the remark that he had not reached with his instrument such a degree of sensitivity which could enable him not only to demonstrate the existence of the minute normal variations of the magnetic field but to measure them, too. But for the determination of the far greater *anomalous variations* the device proved itself to be more then sufficiently sensitive.[6]

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As I have mentioned before, Eötvös did not publish — and even Fekete has given a rather brief explanation of it — how the translatometer could be applied to the determination of the induced and remanent moment of the rocks. Therefore it will be perhaps of some interest if on this occasion I should deal with the matter in a few details basing upon the routine of measurement followed for many decades after the death of Eötvös, too, in the Hungarian Geophysical Institute named after him.

In the course of this application the inclination of the *measuring magnet* is not changed, but it is hanged so that its *axis* be directed permanently *vertically* downwards. Assuming this direction as the direction of the positive z-axis, we have

$$M_x = M_y = 0, \quad M_z = M$$

and the horizontal components of the translational force (exerted upon the magnet of moment M) producing a couple upon the translatometer are:

$$P_x = MX_z$$

$$P_y = MY_z$$

Let a horizontal direction be assumed arbitrarily as the direction of the positive x-axis and let us set the horizontal beam of the translatometer perpendicular to it, so that the direction of the beam showing towards the suspension point of the measuring magnet M, be the direction of the positive y-axis (Fig. 1.) In this case from the components of the translational force exerted upon the measuring magnet it will be only the component

$$P_x = MX_z$$

which produces a couple on the horizontal balance beam. (The horizontal component of the magnetic field, H could also produce a couple, but the value of this would be zero because the moment of the measuring magnet has no horizontal component.)

Taking as origin of the coordinate system the intersection of the suspension wire and the horizontal balance beam and denoting by l the length of the positive half part of the horizontal balance beam, we have for the coordinates of the measuring magnet M (in its centre)

$$x = 0, \quad y = l, \quad z$$

Therefore the torque of the forces acting upon the measuring magnet M relating to the z axis coinciding with the suspension wire is

$$F = xP_y - yP_x = -lP_x = -lMX_z$$

The suspension wire of a torsion-coefficient τ will be twisted owing to the action of the torque by an angle ϑ, this twisting producing an opposite torque of value $\tau\vartheta$, balancing the torque F in case of equilibrium, i. e.

$$\tau\vartheta = -lMX_z$$

Applying the common scale-reading by means of a mirror and denoting the distance of the scale and the mirror by D, the scale-reading corresponding to the equilibrium position, as producing itself in case of a homogeneous magnetic field, by s_0; the reading in case of the position with the twisting by the angle ϑ let be: s, the difference $s - s_0$ let be: n; taking into account that with increasing of the positive value of ϑ the scale reading s diminishes, we get

$$\vartheta = \frac{s_0 - s}{2D} = -\frac{n}{2D}$$

Therefore we have

$$X_z = \frac{\tau n}{2DlM}$$

The factor τ: $2\,DlM$ may be called the sensitivity (more correctly: scale value) of the instrument with respect to X_z; it may be denoted by ε.

With this we have:

$$X_z = \varepsilon n.$$

Now if we have to determine the magnetic moment $\mathfrak{m}(m_x, m_y, m_z)$ of some rock sample or other magnetic body by means of our translatometer measuring the translational action of the inhomogeneous magnetic field of the body, then from the data characterizing the inhomogeneity of the magnetic field of the body we have only to deal with the derivative X_z and we have to express this by means of the magnetic moment of the body, $\mathfrak{m}$, and the data characterizing its position with respect to the measuring magnet.

The *potential of the magnetic field of a magnet* being at the point (ξ, η, ζ) and having the moment $\mathfrak{m}$ can be expressed at the point (x, y, z) as follows:

$$V = -\left(\mathfrak{m}, \operatorname{grad}_{\xi\eta\zeta}\frac{1}{r}\right) = \left(\mathfrak{m}, \operatorname{grad}_{xyz}\frac{1}{r}\right) =$$

$$= m_x\frac{\partial\frac{1}{r}}{\partial x} + m_y\frac{\partial\frac{1}{r}}{\partial y} + m_z\frac{\partial\frac{1}{r}}{\partial z}$$

$$V = m_x\left(\frac{1}{r}\right)_x + m_y\left(\frac{1}{r}\right)_y + m_z\left(\frac{1}{r}\right)_z$$

Therefore

$$X_z = V_{xz} = m_x\left(\frac{1}{r}\right)_{xxz} + m_y\left(\frac{1}{r}\right)_{xyz} + m_z\left(\frac{1}{r}\right)_{xzz}$$

where

$$r = [(\xi - x)^2 + (\eta - y)^2 + (\zeta - z)^2]^{\frac{1}{2}}$$

and

$$\left(\frac{1}{r}\right)_{xxz} = 15\frac{(\xi - x)^2(\zeta - z)}{r^7} - 3\frac{\zeta - z}{r^5}$$

$$\left(\frac{1}{r}\right)_{xyz} = 15\frac{(\xi - x)(\eta - y)(\zeta - z)}{r^7}$$

$$\left(\frac{1}{r}\right)_{xzz} = 15\frac{(\xi - x)(\zeta - z)^2}{r^7} - 3\frac{\xi - x}{r^5}$$

Let us consider two characteristic positions of the body to be investigated; in these cases the expressions for the derivatives of $\frac{1}{r}$ and the derivative X_z itself will be considerably simpler. In one of the cases the body to be investigated will be placed on the *level of the measuring* magnet in the direction of the $+x$ axis; in the other case it is assumed to be *under the measuring magnet* at a given distance from it.

I. In this case the body of a magnetic moment $\mathfrak{m}(m_x, m_y, m_z)$ let be placed on the *level of the measuring magnet* at a *distance* ϱ *from* M *in the direction of the* $+x$*-axis*, the angle of wich with respect of the balance beam is $-90°$, i. e. the coordinates of the body will be

$$\xi = \varrho, \quad \eta = y = l, \quad \zeta = z$$

At this point we have obviously

$$\xi - x = \varrho$$

$$\eta - y = 0$$

$$\zeta - z = 0$$

$$r = \varrho$$

$$\left(\frac{1}{r}\right)_{xxz} = 0$$

$$\left(\frac{1}{r}\right)_{xyz} = 0$$

$$\left(\frac{1}{r}\right)_{xzz} = -\frac{3}{\varrho^4}$$

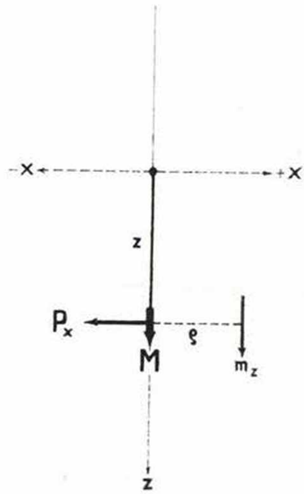

Fig. 2.

Therefore

$$X_z = -\frac{3m_z}{\varrho^4}$$

$$P_x = -\frac{3m_z}{\varrho^4}M$$

and

$$F = \tau\vartheta = -lMX_z = \frac{3Mm_z l}{\varrho^4}$$

We see that in this case the torque F produced as a consequence of a negative gradient X_z and a likewise negative translational force P_x, is positive, further we see that this rotating effect is brought about solely by the *vertical component* of the magnetic moment of the body under investigation.

Let us solve our equation for m_z:

$$m_z = -\frac{\varrho^4 X_z}{3} = -\frac{\varrho^4 \varepsilon}{3} n,$$

and the factor of the elongation n, i. e. the sensitivity (or scale value) of the instrument with respect to m_z denoted by R, then we have

$$R = \frac{\varrho^4 \varepsilon}{3} = \frac{\varrho^4}{3} \frac{\tau}{2DMl}$$

and

$$m_z = -Rn.$$

Thus the magnetic moment of the investigated body pointing vertically downwards may be very simply computed from the observed value of the elongation n, supposing that the characteristic data ε and ϱ are given.

As a rule, the sensitivity-constant ε is not determined by computation — using the data τ, D, M, l —; preferably we get it experimentally, using a magnet of known moment m_z at a given distance ϱ and observing the elongation n. The quantity R will be computed in each case by means of ε and ϱ.

The component m_z of the magnetic moment of the body under discussion is composed of two parts: one of them is the vertical component $\varkappa v Z$ of the magnetic moment *induced* in the body by the actual magnetic field vector $\mathfrak{H}(X, Y, Z)$, the other is the component μ_z of the *remanent* magnetic moment of the body, where we have denoted the magnetic susceptibility of the body by $\varkappa$ and its volume by v. In case of a homogeneous isotropic body the z-component of the induced moment amounts always to $\varkappa v Z$ irrespective of whether that or other direction (axis) of the body should be in vertical position or whether it pointed upwards or downwards. On the other hand the remanent moment $\vec{\mu}$ is a vector bounded to the body, i. e. its vertical component depends on that which axis of the body (and in which direction, upwards or downwards) would occupy the vertical position.

Therefore if we set one of the axes of the body in vertical position and we revert it afterwards by turning the body upside down, the vertical component of the magnetic moment induced in the body remains unchanged, i. e. $\varkappa v Z$, while the vertical component of the remanent magnetic moment of the body reverts its sign however keeping its absolute value. Thus the action of the body exerted upon the measuring magnet of our device is in one of the cases proportional to the *sum* of the vertical components of the induced and remanent moments, in the other to the *difference* of the same two moments.

Let us mark the end of the axis of our body in the positive direction and the elongation brought about by the action of the body if the positive end of the axis dealt with points *downwards*, let be benoted by n_a and in the *reversed* case by n_f. According to the above discussion, we have

$$\varkappa vZ + \mu_z = -Rn_a$$

$$\varkappa vZ - \mu_z = -Rn_f$$

Adding and substracting these two equations and dividing by $2vZ$ resp. by 2, we get the susceptibility $\varkappa$, respectively the vertical component μ_z of the remanent magnetic moment of the body. Denoting the sum n_f+n_a by c, the difference n_f-n_a by d we have

$$\varkappa = -\frac{R}{2vZ}c$$

$$\mu_z = \frac{R}{2}d.$$

In the course of paleomagnetic researches we have to determine the remanent magnetic moment of *oriented rock samples*. We may represent the orientation of the sample, i. e. its position at the original place of occurrence most simply by suitable denoting in the body the ends of the three axes taken parallelly to the geographical coordinate-axes. Then we take the body — keeping a position as mentioned above — nearby the instrument and we set the *marked axes one after another* in *vertical position*, executing two observations in each position (one whith the axis pointing upwards and one by reversing it). We may easily derive the following formulae:

$$\mu_N = \frac{R}{2}d_N$$

$$\mu_E = \frac{R}{2}d_E$$

$$\mu_Z = \frac{R}{2}d_Z$$

where N denotes the northern (positive) end of the x-axis, E the eastern end of the y and Z the end of the z-axis poiting downwards, all three being bounded to the rock body in its position as occupied at the original place of occurrence.

If it may be supposed that the remanent magnetic moment of the rock should be due to the inducing effect of the *magnetic field of the Earth prevailing at the genesis of* the rock, $\mathfrak{H}_0(X_0, Y_0, Z_0)$ and if we may suppose — at least on the average of many samples — that the orientation of the sample-rock has not changed — or only in a way to be taken into account — than we are entitled to assume that the values of μ_N, μ_E and μ_Z are proportional to the one-time components of the magnetic vector, i. e. X_0, Y_0 and Z_0 respectively. The factor of proportionality, the one-time magnetic susceptibility of the rock being unknown we are able to determine only the direction of $\mathfrak{H}_0$, its magnitude remaining indeterminable.

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The magnetic *declination* D_0 and *inclination* I_0 characterizing the one-time field vector will be determined by the folloving formulae:

$$\cos D_0 = \frac{X_0}{\sqrt{X_0^2 + Y_0^2}} = \frac{\mu_N}{\sqrt{\mu_N^2 + \mu_E^2}} = \frac{d_N}{\sqrt{d_N^2 + d_E^2}}$$

$$\sin D_0 = \frac{Y_0}{\sqrt{X_0^2 + Y_0^2}} = \frac{\mu_E}{\sqrt{\mu_N^2 + \mu_E^2}} = \frac{d_E}{\sqrt{d_N^2 + d_E^2}}$$

$$\operatorname{tg} I_0 = \frac{Z_0}{\sqrt{X_0^2 + Y_0^2}} = \frac{\mu_Z}{\sqrt{\mu_N^2 + \mu_E^2}} = \frac{d_Z}{\sqrt{d_N^2 + d_E^2}}$$

It is obvious that the declinational angle D_0 will be determined unequivocally by $\cos D_0$ and $\sin D_0$ and the same is true for I_0 being defined by $\operatorname{tg} I_0$ because the inclination may be only an angle lying always between $-\frac{\pi}{2}$ and $+\frac{\pi}{2}$.

II. Let us set now our body with the magnetic moment $\mathfrak{m}(m_x, m_y, m_z)$ vertically *under the measuring magnet* at a distance ϱ, i. e. to the point with the coordinates

$$\xi = x = 0, \quad \eta = y = l, \quad \zeta = z + \varrho$$

At this point we have obviously

$$\xi - x = 0$$

$$\eta - y = 0$$

$$\xi - z = \varrho$$

$$r = \varrho$$

$$\left(\frac{1}{r}\right)_{xxz} = -\frac{3}{\varrho^4}$$

$$\left(\frac{1}{r}\right)_{xyz} = 0$$

$$\left(\frac{1}{r}\right)_{xzz} = 0$$

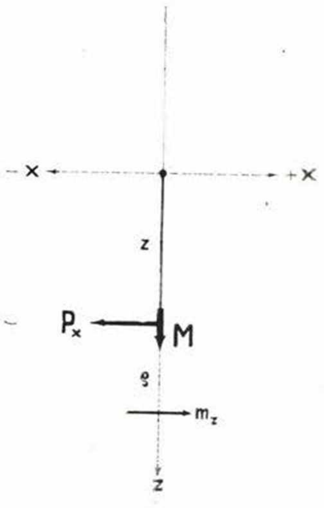

Fig. 3.

Therefore

$$X_z = -\frac{3m_x}{\varrho^4}$$

$$P_x = -\frac{3m_x}{\varrho^4} M$$

and

$$F = \tau\vartheta = -lMX_Z = \frac{3Mlm_x}{\varrho^4}$$

We may see that the torque F originating as a result of the negative gradient X_z and the equally negative translational action P_z, is positive in this case, too. This rotating effect is due also in this case only to one of the components of the magnetic moment of the body under investigation, but now it is not the vertical component which exerts its effect but the *horizontal one in the direction of the x-axis*, m_x.

Solving our equation for m_x we obtain:

$$m_x = -\frac{\varrho^4 X_z}{3} = -\frac{\varrho^4\varepsilon}{3}n = -Rn$$

$$m_x = -Rn$$

The angle of the positive direction of the x-axis with respect to the positive direction of the y-axis is $-90°$; therefore we are now able to determine – knowing ε and the distance ϱ and observing the elongation n, – the component m_x of the magnetic moment of the body placed under the measuring magnet, this component being perpendicular (according to the interpretation given above) to the balance beam.

This component consists of two parts again, of the $\varkappa vX$ *induced and* μ_x *remanent* components of the moment. As to their separation and to the determination of the components of moment μ_N, μ_E and μ_Z as well as of the D_0 declination and I_0 inclination characterizing the *one-time magnetic field of the Earth* the same procedure can be applied as with case I.

It is worth while mentioning however, that if the balance beam be set in the magnetic meridian, then the magnetic field vector has no component in the direction of the x-axis, therefore the body does not possess an induced magnetic moment in the *x-direction*. Thus, in this case the magnetic moments m_N, m_E and m_Z – observed on the oriented rock samples – will furnish themselves the μ_N, μ_E and μ_Z components of the remanent magnetization.

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Galina Nikolayevna P e t r o v a the renowned Soviet researcher of paleomagnetism added a remark to my lecture. Previously she lectured namely at the 9th International Symposium of the Association of Hungarian Geophysicists on the paleomagnetic researches, performed in the Academic Geophysical Institute of Moskow, and presented the diagrams of the variations of the paleomagnetic data in the USSR. Joining to her lecture, I directed her attention to the results of E ö t v ö s' similar investigations. She received Eötvös' data with great interest and plotted these data relating to about the last 500 years on her diagram, then discussing on my lecture, she showed on the screen the completed diagram. A good accordance became visible, if one considered the lag due to the „westward drift" in the secular variation of the geomagnetic elements. The negative inclinations found by E ö t v ö s (and F o l g h e r a i t e r) for the age B. C. awoke especially her attention, as for lack of soviet data for that age, she interpolated on the basis of earlier data found by Japanese researchers, on *positive level*. This is the reason, why should it be important, if additional investigations were corroborate the reality of Eötvös' negative data. It should mean that the 5 to 600 years period of the variation in the inclination should be considered as an oscillation of a shorter period superimposed on the larger variation of about 5000 years.